d10 Convergent plate boundaries <oceanic trenches, calc-alkaline magmas>

> The prevailing [early seventeenth century] wisdom about bodies in water held that ice was heavier than water, but that broad, flat-bottomed pieces of ice floated anyway because of their shape, which failed to pierce the fluid surface [in the manner of tray-like rafts of heavier than water common salt that form and float on the surface of ponded evaporating seawater]. Galileo knew ice to be less dense than water, and therefore lighter, so that it always floated, regardless of its shape. He could show this by submerging a piece of ice and then releasing it underwater to let it pop back up to the surface. Now, if shape were all that kept ice from sinking, then shape should also prohibit its upward motion through water—and all the more so if ice truly outweighed water. —Dava Sobel *Galileo' Daughter*, 1999.[1]

Away from the ridge, a tectonic plate of oceanic lithosphere cools from top down to achieve beyond an age of ~30 my an overall density greater than the 3100 kg m^{-3} of the underlying mantle.[2] But, being a plate, it cannot sink straight down. However, being flexible, it can turn down at an edge and sink (subduct) along that edge. The downgoing lithosphere is called a *slab*. The slab-weight pulls on the trench edge of the plate that slides horizontally to that place where it subducts. Slab-plate coupling varies from near total to near zero.[3] The slab interface with the under-ridden plate is a megathrust that in its shallow part locks and intermittently slips to release great earthquakes. Lower magnitude earthquakes are released from within the descending slab when, beginning below 10-20 km depth, water is "squeezed" from carried-down hydrated minerals (as amphibole) which recrystallize as water-free minerals. Dehydration of serpentinite and chlorite is also inferred to result in arc magmatism and intermediate-depth (50-300 km) self-localizing thermal runaway earthquakes.[4] In their plunge, some subducting slabs also sink broadside (***Figure d10.1***).[5] Deep earthquake hypocenters (foci) were first demonstrated in 1927 by Kiyoo Wadati.[6] By 1935, he had shown that earthquake foci deepen in their occurrence from the Ryukyu trench along an inclined surface that dips WNW beneath Japan to deep beneath the Asian continent.[7] In 1954,[8] Hugo Benioff (1899-1968) found similarly for concentrations of earthquake foci down an inclined "Benioff zone," as this was called after 1955 (and correctly now the *Wadati-Benioff zone*) beneath the Kamchatka Peninsula island arc from near-surface at the oceanic trench to seismic-recorded depths of 680 km.[9]

At Earth's surface, *convergent* plate boundaries are marked by an oceanic trench and a collinear volcanically active fold-mountain belt where calc-alkaline igneous rocks originate.[10] The intrusive/extrusive igneous rocks are: diorite/andesite, monzonite/latite, and granite/rhyolite.[11] The prospectors claim that: "there's gold in them thar hills" is not an idle one for 40% of the total metal-mine value output around the world is obtained from such Cenozoic and Mesozoic orogenic belts. Most of the ore in the upper crust is of hydrothermal origin. A scenario for the origin of this ore derived from subducted oceanic crust, described by Gaelle Prouteau and others in 2001, is: Initially, pyroxene-bearing plutons accumulate in the lower crust from magmas rising from a steep subduction zone. Shallowing of the subduction zone places the crust under compression. This thickens it, and in the higher pressure lower part, water, which would otherwise pass through, metasomatises clinopyroxenes to amphibole and garnet.[12] This primes the pump, as it were, for hydrothermal ore mineralization of the upper crust. This occurs when further thickening of the lower crust results in the release of water from amphibole that under the increased pressure and temperature crystallizes to garnet. Copper, molybdenum, and tin ores are often associated with igneous rocks that are porphyritic, which indicates multistage partial melting and partial cooling derivation of the magmas (***Figure d10.2***). Hydrothermal activity enters at various stages of both prograde and retrograde metamorphism of the country rock. Where porphyries intrude Paleozoic sedimentary carbonates, igneous metamorphic-metasomatic similar base metals and ores of tin-Sn, tungsten-W, and iron-Fe, deposits, called *skarns* (also called: *tactites*), occur. Pegmatites and veins originating from porphyry are associated with country rock replacement and fault open-space infilling hydrothermal base metal ores. Of like type are base metal and precious metal (gold-Au and silver-Ag) ores that occur at such distances from possible source igneous rocks that the clear association can only be inferred. These are named Cordilleran Vein type by F. J. Sawkins in 1972 for where he discerned their origin.[13] They are typically deposited within about 1 kilometer of the surface where meteoric waters determine the late stages of vein deposition. Not surprisingly, these high-level deposits are not found in deeply eroded terrains of old mountains (although some of the oldest mines in the world are, as is so of the silver mines at Laurium, Greece, that for centuries funded Athenian city states).[14] ❑

Figure d10.1

Cross section of Earth's crust and upper mantle, showing a subducting slab of oceanic lithosphere that both plunges and sinks broadside. The latter motion causes an overriding continental plate to be drawn forward in the direction of the rollback of the downbend of the subducting slab.[15]

"Grease" for the upper edge of the downgoing slab can be provided at intermediate depth by serpentinization of the overlying mantle by upward-migrated water released by pressure-dehydration of the entrained material and any prior-serpentinized upper edge of the subducting lithosphere.[16] *However*, for 57% of convergent margins' total length today, subducting slabs abrasively corrode causing secular subsidence and 1-3 km/my narrowing of forearcs.[17] Such an erosive margin (of Tertiary age) is exposed for inspection in the Northern Apennines of Italy.[18]

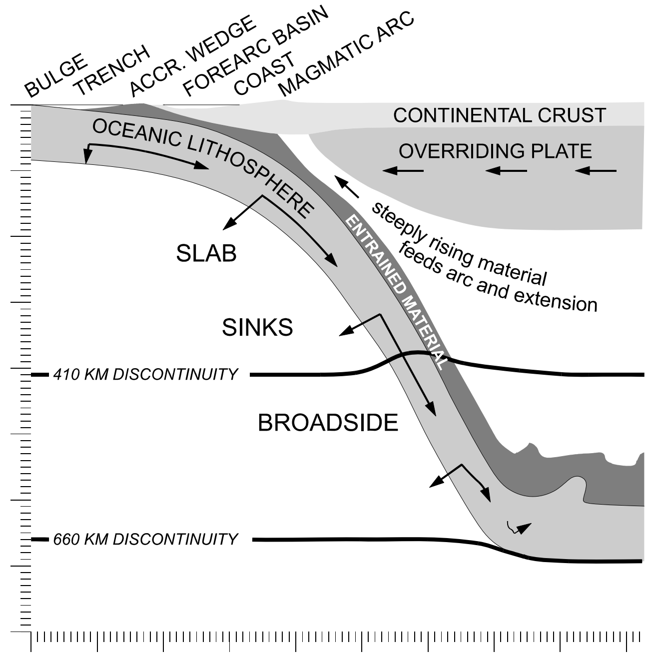

Figure d10.2[19] **Variation of some common ore metals in igneous rocks**

Abundances in parts per million (small numbers along graph lines) are plotted normalized (grid horizontals) with respect to the whole crust.

The succession of igneous rocks: ultramafic to mafic, to intermediate, to granitic, and to syenite, can be explained by the repetition of partial melting, upward escape of the melt, and cooling to rock. In the process: chromium-Cr, and nickel-Ni, are left behind in the unmelted rock; uranium-U, and lead-Pb, move out with each melt and so become concentrated; and, copper-Cu, silver-Ag, molybdenum-Mo, and tin-Sn, move with the initial melts and then become extracted by hydrothermal mechanisms.